HEAVY ION BOOSTER CYCLOTRON DESIGN STUDIES AT BERKELEY*

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Abstract

Design studies on four booster cyclotrons for heavy ions are described. Comparisons are made of normal vs. super conducting main coils, and K = 400 and 800 sizes. Performance and cost estimates are given.

Introduction

In the past several years interest throughout the world has increased greatly in the new frontier of heavy ion nuclear science and medicine. New accelerator projects are in the planning or construction stage in many countries as described at this conference. At LBL we have been investigating the options for increasing our range of heavy ion particles and energies. The present heavy ion accelerators at LBL are the SuperHILAC, the Bevatron and the 88-Inch Cyclotron. The Bevatron output has recently been upgraded significantly by injecting it with the SuperHILAC. This combination of accelerators is called the Bevalac. In Fig. 1 the solid lines show the performance of these existing accelerators when developed to their full potential. The regions inaccessible to our present machines are the energy region above the 88-Inch Cyclotron and the SuperHILAC but below the Bevalac, and the heavier mass region at Bevalac energies. In this paper we explore some of the options for using single pole cyclotrons as boosters (post-accelerators) for the SuperHILAC and the 88-Inch Cyclotron. The cyclotron has the desirable characteristic of 100% macroscopic duty factor. Since this cyclotron study was done it was decided that the highest priority for a proposal at LBL for heavy ion beam expansion is in the extension of the Bevalac to heavier ions and lower energies ("Improved Bevalac", Fig. 1), and increasing the SuperHILAC intensity for heavier masses. A more detailed account of design and preliminary cost estimates is given in an LBL internal engineering note.[1])

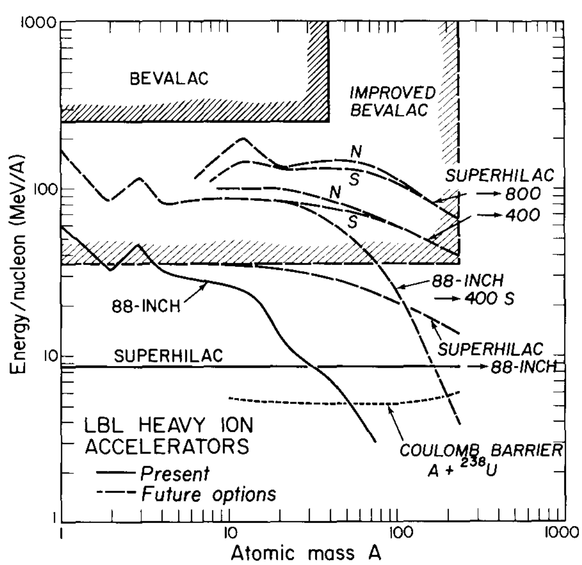

Fig. 1. Performance predictions for present and possible future LBL heavy ion accelerators.

Design Options

There are several types of sector-focused cyclotron designs which can be used. These are illustrated schematically in Fig. 2. The four cases show relative sizes of cyclotrons with either a single pole or separate sectors, and with either normal-conducting or super-conducting coils. These cases all have the same K or maximum bending strength. The pole diameter is about twice as large for the separate sector as for the corresponding single pole design, because of the smaller average field around the orbit. The pole diameter is about 3 times as large for the normal-conducting as for the corresponding super-conducting machine, since the field is 3 times lower. The peak field for the normal conducting cases is 1.7 T. The field in the return yoke is 1.7 T for all cases. The beam injection and extraction would be easier in the separate sector Cases 1 and 3, but they are more expensive than Cases 2 and 4. Injection would be by a stripping foil to get the beam across the magnetic field in Cases 2 and 4.

For this study Cases 2 and 4 were chosen because of their lower cost compared to Cases 1 and 3.

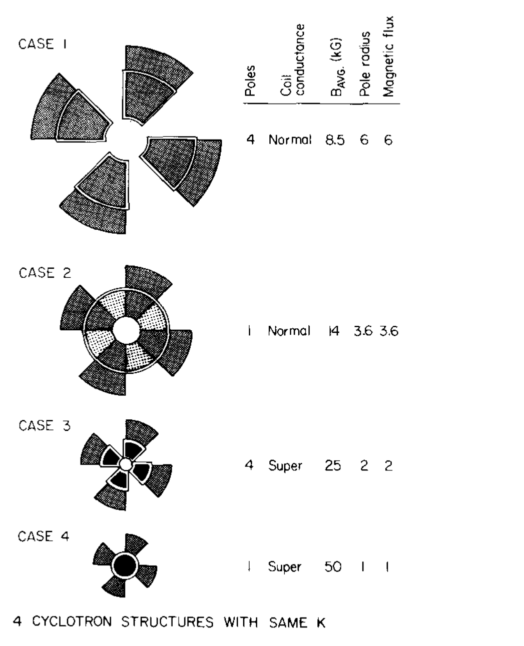

Fig. 2. Four cyclotron structures with the same K value or bending strength.

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Case 4 is interesting because of its small size and resultant low cost. The extraction is a special challenge because of the 5.0 T field level in the pole. The sizes chosen are K = 400 and K = 800 for each case, where K is the energy constant in the equation $E = KQ^2/A$ where E is maximum energy, Q and A are particle charge and mass in proton units. In the following sections the letters S and N follow the K to denote super-conducting or normal-conducting main coils. Table 1 lists the specifications of the 4 designs studied.

Case 2: Normal-Conducting, Single Pole

A schematic design for a 400 N booster cyclotron is shown in Fig. 3. Four magnet return legs are used to reduce the amount of steel. A high average field of 2.0 T is used to minimize the size and cost. This is similar to the field used in the UCLA 50 MeV cyclotron. The field in the yoke is 1.7 T. The vertical yoke profile is contoured to minimize weight. An extractor is shown schematically only.

The RF system has 2 dees in the valleys to minimize magnetic gap. The hill gap is 5 cm --large enough to withdraw the dee system without raising the upper magnet yoke. Harmonics are 2-4 which give high energy gain/turn with 45 degree wide dees. The energy range is then covered with an RF frequency range of 2 to 1.

The coils are tape wound with slots for the dees and injection and extraction channels. This construction gives good magnetic field out to large radius, and fast fall-off for easier extraction. A lifting system for the upper yoke would be used for installation and maintenance of the deflection system.

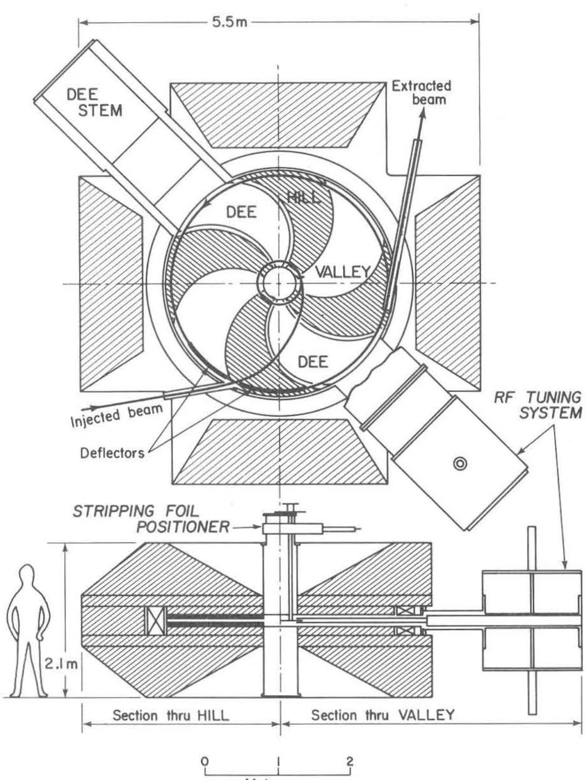

Fig. 3. The 400 N booster cyclotron.

A larger version of this design, the 800 N was also studied. The linear dimensions are scaled up a factor of $\sqrt{2}$ from the 400 N.

Case 4: Super-Conducting, Single Pole

Schematic plan and elevation views of a 400 S cyclotron are shown in Figs. 4 and 5. This design was described at a symposium held in Montreal,

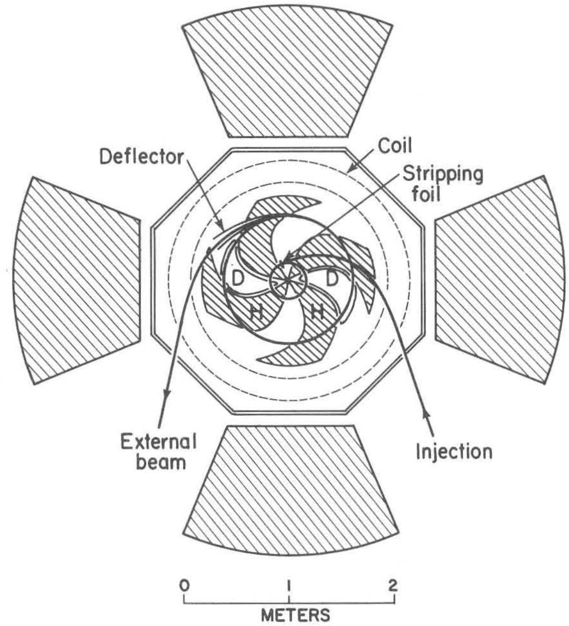

Fig. 4. Plan view of the 400 S cyclotron.

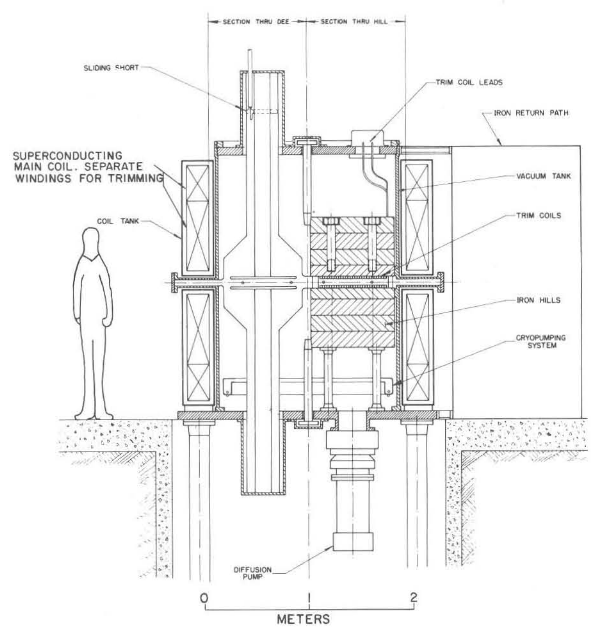

Fig. 5. Elevation view of the 400 S cyclotron.

Table 1. Specifications

		400 S	400 N	800 S	800 N
K		400	400	800	800
Mag. Field (T)	Hill	5.5	2.4	5.5	2.4
	Valley	4.5	1.6	4.5	1.6
	Average	5.0	2.0	5.0	2.0
Extraction Rad. cm		61	149	86	210
Pole Dia. cm		127	312	178	436
Hill Gap cm		5	5	5	5
Injection Rad. cm		13	30	18	42
Main Vacuum Torr		5×10^{-8}	5×10^{-8}	5×10^{-8}	5×10^{-8}
Dee Voltage kV		100	100	100	100
RF Frequency MHz		66 - 44	30 - 15	64 - 43	15 - 7.5
Harmonic No.		2 - 5	2 - 4	2 - 6	1 - 3
Magnet Wt. 10^5 kg		1.2	3.2	3.4	9.1

Canada in Dec. 1973. The specifications are shown in Table 1.

The super-conducting coil provides 5.0 T average field in the bore. It has a geometry similar to that of large bubble chamber coils. Argonne National Laboratory, U.S.A. has built a "15 foot" bubble chamber coil[2]) with an inside diameter of 14 feet (4.3 m), a central field of 3.0 T and a maximum field at the coil of 5.0 T. The coil in the 400 S cyclotron is 1.9 m inside diameter and has a maximum field at the coil of 5.0 T with some iron just inside the coil for shielding. Thus it is well within current engineering practice.

Each coil is shown split into an upper and lower section for trimming the radial field profile. An example of the field control available with this type of division of about 1/3 to 2/3 is shown in Fig. 6. This is a plot of the field on the median plane of a cylindrical coil without iron. With coil B energized at uniform current density the field profile rises about 5% more than when coils B and C are both energized. 5% represents about 50 MeV/nucleon difference in energy, and so we have a powerful method of radial field control for variable energy, thus saving power in normal-conducting trim coils on the pole face. For the real machine suitable iron would be used in the bore to raise the field at the edge as well as to provide flutter. The third curve in Fig. 6 of a coil completely across the median plane indicates the value of having the coils close together by showing the large radial extent of good field and the sharp fall-off, which eases the extraction.

Flutter in the magnet is provided by saturated steel sectors supported inside the super-conducting coil bore. The field in the saturated steel is 2.0 T higher than in the space between sectors. But in a practical geometry the hillvalley difference on the median plane is typically 1.0 T. Calculations of the flutter from several gap configurations were made using the program TRIM. This program calculates the field due to a two-dimensional array of iron having any desired saturation properties. In this case a saturation value of 2.0 T was assumed. Average field levels were 5.0 T, so the iron is

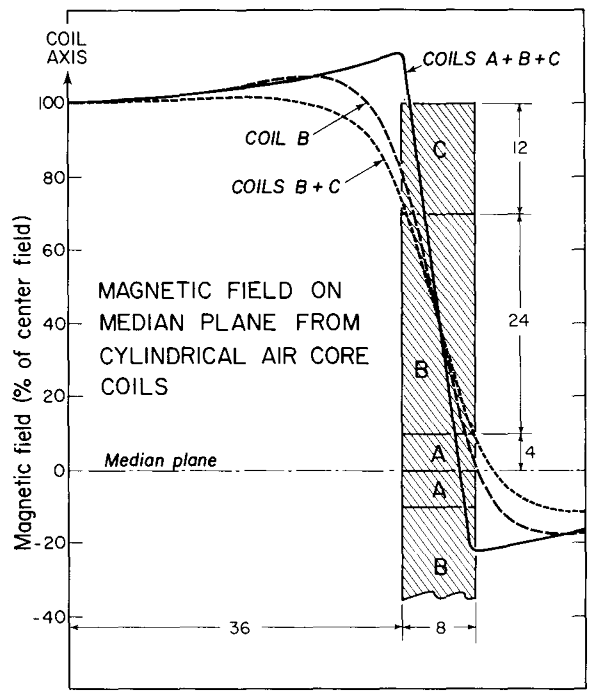

Fig. 6. Magnetic field of several coil combinations.

completely saturated. The following table shows some of the values of ΔB_{rms} obtained. 2g is the hill gap, f_H the hill fraction, L the "wavelength" or azimuthal distance through one hill and one valley, and ΔB_{rms} the flutter.

Table 2. Flutter For Several Iron Configurations

2g	f_H	L	ΔB_{rms}(T)
2.0	.5	12	.55
	.31	8	.36
		12	.44
3.5	.5	8	.22
		20	.53

Accuracy is ±.01 T. These cases have a hill height about equal to the wavelength, so the flutter is .01 - .02 T lower than for infinite hill height.

The injection is again by stripping at the first orbit. Extraction will require a powerful magnetic channel.

The dees are supported by dee stems coming in axially in two of the valleys. This is a natural configuration since the valleys are empty and there is little space for dee stems between the main coils, which need to be close together for a good magnetic profile.

The vacuum system is a cryopump, which is supplied with cold helium gas by a small fraction of the refrigeration used for the main coil. A small diffusion pump or turbo-pump can be used to pump hydrogen and helium.

In the version of this type of cyclotron proposed by Michigan State University Cyclotron Laboratory, U.S.A.[3] the coils are closer together, making the main coil smaller for the same maximum beam radius, due to a better radial field profile. Also a top and bottom yoke are added for better stray field containment. In the Table 1 specifications and Table 3 cost estimates, the improved MSU design is assumed.

An 800 S version of this design uses the same style but is scaled up in linear dimensions by $\sqrt{2}$.

Injection Conditions

For successful cyclotron operation with injection across the magnetic field there must be sufficient charge change at the stripping foil to place the beam in a small first orbit, so that there can be significant energy gain out to full radius. The maximum ratio of extraction to injection energy, E_E/E_I, is calculated for injected charge Q_0 and accelerated charge Q_1. R_E is extraction radius and F is the width of the fringing field.

$$E_E/E_I = \left(\frac{R_E}{R_E + F}\right)^2 \left(\frac{Q_1}{Q_0}\right)^2 \left(2 - \frac{Q_0}{Q_1}\right)^2 .$$

The limiting case is calculated where the injected beam is just tangent to the outer field boundary. In the actual case the beam could be injected in along a valley and at an angle larger than 0° to the field edge. This formula serves as a useful design guideline to determine the injection limitations on maximum beam energy for various cyclotron designs.

Performance

The estimated performance of each option with injection from either the SuperHILAC or the 88-Inch Cyclotron is shown in Fig. 1. Since the SuperHILAC produces higher energies for ions with A > 30, it makes a better injector than the 88-Inch. The gain in going from a K of 400 to 800 is not great. The super-conducting and normal-conducting versions have similar performance. An interesting option is injecting the 88-Inch with the SuperHILAC. The machines are assumed not to be limited by extraction. The focusing limit is an optimistic estimate based on data from H. G. Blosser[4]. The intensities are in the region of 10^{14} - 10^{11} particles/sec going from light to heavy ions, with the cyclotrons and the SuperHILAC. They are 10^{10} - 10^{7} particles/sec for the Bevalac.

Cost Estimates

Cost estimates for the 4 designs studied are shown in Table 3. They include engineering and construction of the cyclotron, but not shielding, beam transport or building. The costs are based on standard LBL construction account rates. The lowest cost option is the 400 S, and its performance is very good in Fig. 1. This is why this style of design is of interest to several laboratories.

Table 3. Cost Summary: U.S. k$ 12/74

	400 S	400 N	800 S	800 N
A. Magnet Core	300	750	700	1,800
B. Main Coil	700	255	1,210	372
C. Trimming Coils	220	1,200	430	2,225
D. Vacuum System	180	600	300	880
E. Injection System	90	130	120	176
F. Extraction System	170	425	225	600
G. R. F. System	800	2,250	1,100	4,400
H. Probes, etc.	120	270	170	377
*I. Mag. Meas.	200	600	390	920
J. Controls	450	550	500	700
K. Cooling Water	120	150	150	200
L. Mag. Separation	200	300	350	450
M. Building	-0-	-0-	-0-	-0-
N. Shielding	-0-	-0-	-0-	-0-
O. Sum A. thru N.	3,550	7,480	5,645	13,100
P. Misc. - 10% of O.	355	748	565	1,310
Q. O. plus P.	3,905	8,228	6,210	14,410
R. Contingency ~25% of Q	976	2,057	1,552	3,602
†S. Min. Est. Cost: Q + R	4,881	10,285	7,762	18,012

*Includes Magnetic Measuring Equipment and Magnetic Measurements.
†Maximum estimate cost is 1.4 times minimum estimate cost.

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References

1. L. R. Glasgow, LBL Engineering Note M4781, 11/74.
2. J. Purcell et al., ANL/HEP 7215, 2/73.
3. H. G. Blosser and M. M. Gordon, MSUCP-28, 7/74.
4. H. G. Blosser, private communication.

DISCUSSION

F. RESMINI: In the case of the K = 400 superconducting cyclotron could you comment on the cost of the major items which add up to 4.9 million dollars.

D.J. CLARK: The major items are the magnet and RF systems. The detailed breakdown of costs is shown in the paper.

G. DUTTO: Could you give more details about how you would perform the extraction in the case of the K = 400 superconducting cyclotron?

D.J. CLARK: We did not make any detailed extraction studies, but optimistically assumed that a strong channel can be developed to extract any beam which can be accelerated.